# EVALUATION OF THE ACCURACY OF 3D DATA ACQUISITION TECHNIQUES FOR THE DOCUMENTATION OF CULTURAL HERITAGE

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## ABSTRACT

In this paper, the accuracy of 3D models of both laser scanning and photogrammetry is discussed for terrestrial applications. The models constructed by photogrammetry are based on digital stereoscopic restitution and structure from motion. These models, and the models generated by processing laser scanning data, are statistically compared with topographic measurements by a total station. The 'Sint-Baafs' Abbey (Ghent, Belgium) is used as a test case in this paper. This historic site contains a series of buildings and ruins, and from these objects, a number of exterior walls are selected for virtual 3D reconstruction. Firstly, the outlines and characteristic points of these walls are measured by a total station. Secondly, a series of extra targets are measured with total station as well, in order to correctly orientate and register multiple point sets from the terrestrial laser scanner. Based on previous research in comparable projects, the angular resolution of the laser scanner must be at least equal to the image resolution, and the distance between the scanner and the wall should be limited. Using the phase-based *Leica HDS 6100* laser scanner, the angular resolution was set to 20 mgon, and the distance between the scanner and the walls was limited to 15-20 m. Thereafter, the walls are photographed with a high resolution digital camera. The acquisition points of the images were not recorded, but the measured characteristic points on the walls are used for orientation of the images and for the 3D geometry derivation from the images. The different images and laser scanning data sets were processed independently, using the total station data as geometric reference. In order to compare the final results, an extra series of check points from this total station were used. An iterative closest point algorithm is also performed to compare the models.

## INTRODUCTION

Laser scanning and photogrammetry are both very useful and reliable techniques for the documentation of cultural heritage and archaeological objects. Terrestrial laser scanning is applied in a large variety of applications where dense point sets with a high accuracy are required. The construction of 3D models by photogrammetry requires indirect derivation of geometries by stereoscopic or multiscopic restitution or bundle adjustment. Although the methods of acquiring data from both sensors differ significantly, they are both intensively used for the generation of high quality 3D models. These models can be used for renovation, visualization or further analysis of the object.

The research presented in this paper covers a geometric accuracy assessment of terrestrial laser scanning (TLS) and terrestrial photogrammetry (TPH) in relation to each other and in relation to conventional topographic measurements. TLS and TPH are frequently used in an integrated manner for the documentation, reconstruction and management of archaeological sites and cultural heritage [1, 2].

Conventional image processing workflows in TPH, resulting in orthorectified images and accompanying 3D envelope models are considered to be very useful for the reconstruction of all kinds of vertical constructions, because of their relatively high geometric quality [3]. However, conventional TPH techniques are time consuming, especially when the used workflows are only compatible with single stereo couples. In contrast, structure from motion (SfM) enables the fast construction of image based 3D models by processing large images sequences at once in one workspace. This procedure has already proven its advantages in archaeology and cultural heritage [4, 5]. Despite of these differences, both conventional TPH and SfM-based TPH have the ability to register high resolution radiometric information of the measured object, which is a big advantage in relation with TLS. TLS is more recent than TPH, but is nevertheless very useful for the fast acquisition of a huge amount of accurate detail points of an object of interest. This acquisition technique is not only used in archaeology, but is well known in civil engineering, e.g. in the detection of changes in constructions [6, 7]. The points, measured by TLS, contain 3D coordinates, and are possibly supplied with an intensity value or, when an internal or external camera is present, a RGB colour value. However, it is important to mention that TLS is not an image generating acquisition technique, but it is notwithstanding an accurate technique for geometric modelling. The integration of TLS and TPH is therefore very feasible for the construction of textured 3D models with both high geometric accuracy and radiometric resolution [8, 9].

With a variety of terrestrial 3D modelling techniques, there is a need for a quality assessment of these techniques. Based on previous work, the comparability of TLS and conventional TPH already became clear, based on topographic measurements. In this paper, the same study is extended with the quality assessment of SfM-based models. The TLS data is processed using *Leica Cyclone* (http://hds.leica-geosystems.com), whereas the SfM-based models are constructed using *Agisoft PhotoScan* (www.agisoft.ru).

## STUDY AREA

This study is part of the full 3D documentation of the cultural heritage site of the former ‘Sint-Baafs’ Abbey at Ghent, Belgium (51°03’13’’N - 3°44’10’’E). The site dates from the 7th century A.D. and was founded by the Aquitanian monk named Amandus [10]. The abbey was flourishing in the 11th century, but suffered intensively from Viking invasions in the 9th century. Large parts of the site were replaced by a Spanish citadel in the 16th century by Charles the fifth. The current state of the site consists of the ruins of the abbey, the refectory, the lavatorium and the courtyard (Figure 1).

*Figure 1: Current state of ‘Sint Baafs’ Abbey (source: Bing Maps)*

In the context of the cultural and ecological recognition of the site by the city of Ghent, the site was documented by the construction of a 3D model using different terrestrial sensors. This work started in 2008 as a collaboration between the city of Ghent and Ghent University, Department of

Geography. Initially, the research involved the quality control of topographic and photogrammetric data, in comparison with different terrestrial laser scanners [11].

## DATA ACQUISITION

### Terrestrial laser scanning

Terrestrial laser scanning (TLS) is a relatively new surveying technique, where a large amount of accurate detail points of an object of interest is acquired. This point set is generated by transmitting an electromagnetic signal over a known and registered horizontal and vertical angle. The transmitted signal is reflected by the object and this signal is received by the scanner. Pulse-based scanners will derive the distance between the scanner and the scanned object from the half of the time of flight, multiplied by the speed of light. Phase-based scanners will derive the distance between the scanner and the measured object based on a phase difference of the reflected signal and a reference signal [12]. In both cases, the relative Cartesian coordinates of each point are calculated using the calculated distance in combination with the registered horizontal and vertical angles [13]. Terrestrial point sets are frequently georeferenced using a target based registration. Static TLS is intensively used to model objects with a limited size and with a limited distance between the object and the scanner [14].

In previous studies on the use of TLS for cultural heritage documentation in Ghent (Belgium), different laser scanners were tested, like a *Trimble GX*, a *Leica ScanStation 2* and a *Leica HDS 3000*. With the start of the 3D modeling project of the 'Sint Baafs' Abbey, a *Leica ScanStation 2* was used for the construction of a point set. This pulse-based scanner has a scanning speed of 50 000 points per second and an internal camera for the assignment of an RGB color to each point. The registration of the different scanning positions resulted in the point set as illustrated in Figure 2. Next to visualization purposes, the final point set, together with TPH-based reconstructions and topographic measurements, were used for a quality assessment. After the first phase of the project, it was concluded that TLS did not meet the accuracy of conventional TPH. The chosen point density of three to four centimeter seemed to be too course in relation to the image resolution of a few millimeter.

*Figure 2: RGB coloured point cloud from Leica ScanStation 2 of the 'Sint Baafs' Abbey (2009)*

In the last phase of the project, a *Leica HDS 6100* laser scanner has been used for the re-measurement on some walls in the abbey (Figure 3). This phase-based laser scanner has a much higher scanning speed of up to 500 000 points per second. This enables higher point densities of one point each 5 mm in a shorter time frame on limited distances of 15 meter. In contrast with the first stage of the project, this point density corresponds with the resolution of the images.

*Figure 3: Leica HDS 6100 laser scanner in the 'Sint Baafs' Abbey*

**Terrestrial photogrammetry**

In the previous research papers, the TLS-based point set was statistically compared with topographic measurements and conventional TPH. In the TPH processing chain, images were processed in a stereoscopic way. This workflow is well known for these kinds of applications in terms of accuracy and acquisition price. However, the processing is time consuming and a faster image based 3D reconstruction technique is desirable.

Thus, new images were taken with a *Canon EOS 1Ds* digital single lens reflex camera. A 24 mm or 35 mm lens was used with this 11 megapixel camera, as a function of the distance between the acquisition point and the wall to cover. As with images for conventional TPH, these new images must have enough overlap (60-80%) between each other. Thereafter, the images are processed in a workflow, using structure from motion (SfM). SfM is a technique in computer vision to acquire 3D geometry from 2D images [15]. Assuming a set of images, where each point of the study object is projected on multiple overlapping images, the 3D position of each point can be calculated by solving a system of geometrical projective matrices. The distance between the different acquisition points must be non-zero. For this study, an uncalibrated camera is used and the true position and orientation of the camera as well as the lens distortions are unknown, so each point has to be projected on at least three images. The projection of a 3D object on a 2D image plane and the inverse transformation of 2D image coordinates to 3D modelling object coordinates, require the extrinsic and intrinsic camera parameters [16]. The intrinsic parameters, like the focal length and the image dimensions, will be taken from the metadata of each image (EXIF). The extrinsic transformation parameters can be calculated by sparse bundle adjustment, supported by the detection of matching points on the images. This set of matching points is generated by the detection of characteristic points in each image. Thereafter, characteristic points in different images are matched with each other, using a least square algorithm. Based on the transformation parameters of the final point set, the acquisition parameters of each image can be calculated. The actual geometric reconstruction is performed by the projection of pixels from each image in a 3D space. The intersections of the projected pixel rays define the nodes of the 3D mesh. Finally, the images are draped over this 3D mesh, in order to generate a high resolution textured virtual reality.

This texture also facilitates the determination of GCPs on the reconstructed wall and thus the absolute orientation of the model. A sample of the generated 3D model is presented in Figure 4.

*Figure 4: Screenshots of the SfM-based 3D model*

**Geodetic framework and reference set**

A series of base points are materialized and measured with a RTK GNSS antenna (*Trimble R-series*) in the Belgian Lambert 72 coordinate system, using FLEPOS (FLemish POsitioning System). The theoretical accuracy of this network solution is between 1 and 2 cm [17]. Based on these points, a polygon in and around the site is constructed, using total station measurements (*Trimble S6* and *Pentax R-series*). The same total stations are used for the measurement of a large number of ground control points (GCPs). The GCPs are used to fit both the TLS point set and the SfM-based 3D model in the absolute reference system. On the one hand, the GCPs for the TLS registration were materialized by black and white targets. Since the *Leica HDS 6100* laser scanner measures the intensity values of the reflected signal, the midpoints of these targets are accurately determined. On the other hand, the GCPs for the SfM-based models were measured, based on highly distinguishable, but not explicitly materialized points on the walls. These characteristic points could be edges of bricks or points with large radiometric contrast with the environment.

Next to the measurement of the GCPs, a series of 16 check points were measured. These points were not used for the referencing of the data, but for the statistical quality analysis. Because of this independence, the error, caused by the absolute positioning of the model using RTK GNSS shall not have an influence on the quality assessment of the data. For these check points, a series of characteristic points were selected, covering the entire extent of the 3D model. In the data analysis, these points are assumed to be the ground truth.

**RESULTS**

After processing the topographic data, the TLS point set and the SfM-based 3D model, three sets of check points were generated by identifying these check points in each data set. The resulting coordinates showed a certain deviation, which was used for the actual accuracy assessment. Each series of check points was used for a pair wise comparison. Thus, the topographic measured check points were compared with check points derived from the terrestrial laser scanning point set (TLS) on the one hand and with check points derived from the SfM-based model (TPH) on the other hand. The mean absolute errors and the standard deviations are presented in Table 1.

*Table 1: Results of the current check point comparison (values in meter)*

| Current | | | | | | |
|---|---|---|---|---|---|---|
| | | X | Y | Z | 2D | 3D |
| Mean absolute error | Topography - TLS | 0.013 | 0.023 | 0.023 | 0.029 | 0.038 |
| | Topography - TPH | 0.010 | 0.009 | 0.008 | 0.015 | 0.018 |
| | TLS - TPH | 0.014 | 0.022 | 0.017 | 0.027 | 0.033 |
| Standard deviation | Topography - TLS | 0.010 | 0.022 | 0.011 | 0.021 | 0.021 |
| | Topography - TPH | 0.007 | 0.008 | 0.004 | 0.008 | 0.007 |
| | TLS - TPH | 0.010 | 0.015 | 0.010 | 0.015 | 0.016 |

These results indicate an equal distribution of the errors in the X, Y and Z direction. The mean absolute error and standard deviation between the topographic measurements and the TPH-based 3D model are the lowest, while the mean absolute error and standard deviation between the topographic measurements and the TLS point set are the largest. Although the TLS point set is generated with a point density comparable to the image resolution, the standard deviations of the TLS comparisons are three times the point density, whereas the topography-TPH comparison is only one or two times the image resolution. It is interesting to compare these results with the previous research [11]. The mean absolute errors and standard deviations are presented in Table 2. Some important reasons for possible differences between these results and the new results must be mentioned before further interpretation of the results:

- The results from [11] are based on a project with many participants, meaning that possible errors in the data could be caused by the operators heterogeneity. In contrast, the new results presented in this paper are all acquired and processed by the same person;
- The TPH-based results in Table 1 are extracted from SfM, while the TPH-based results in Table 2 are extracted from a conventional photogrammetric workflow, using a large series of stereoscopic images and a VirtuoZo workstation;
- Neither the different current data set and the previous data set have the same geodetic framework, GCPs and check points, nor do they cover exactly the same façade. However, it is assumed that this does not have a significant influence on the quality analysis, since the same procedure is used for the absolute referencing. A pair wise comparison between the current and previous data sets is therefore not possible.

*Table 2: Results of the previous check point comparison (values in meter)*

| Nuttens *et al.*, 2011 | | | | | | |
|---|---|---|---|---|---|---|
| | | X | Y | Z | 2D | 3D |
| Mean absolute error | Topography - TLS | 0.009 | 0.005 | 0.003 | 0.011 | 0.011 |
| | Topography - TPH | 0.010 | 0.003 | 0.016 | 0.010 | 0.019 |
| | TLS - TPH | 0.019 | 0.002 | 0.018 | 0.019 | 0.027 |
| Standard deviation | Topography - TLS | 0.015 | 0.017 | 0.013 | 0.023 | 0.027 |
| | Topography - TPH | 0.027 | 0.029 | 0.031 | 0.040 | 0.050 |
| | TLS - TPH | 0.030 | 0.036 | 0.032 | 0.047 | 0.057 |

The results of this table are clearly explained in [11], but a fast comparative interpretation with the new results becomes clear by Figure 5. In this figure, the circles represent the absolute means for each comparison and the lines represent plus and minus one time the standard deviation, corresponding with 68 % of the observations, assuming a normal distribution.

The equal standard deviation of the topography-TLS comparison states the coherence between the two data sets and thus justifies the use of this previous data set. The highest correlation between the two sets occurs with the comparison between the topography and TPH. The lowest repeatability occurs with the TLS-based comparisons. The standard deviations of the TPH-based results are lower than the standard deviations of the previous research. However, the differences between the absolute means are less obvious.

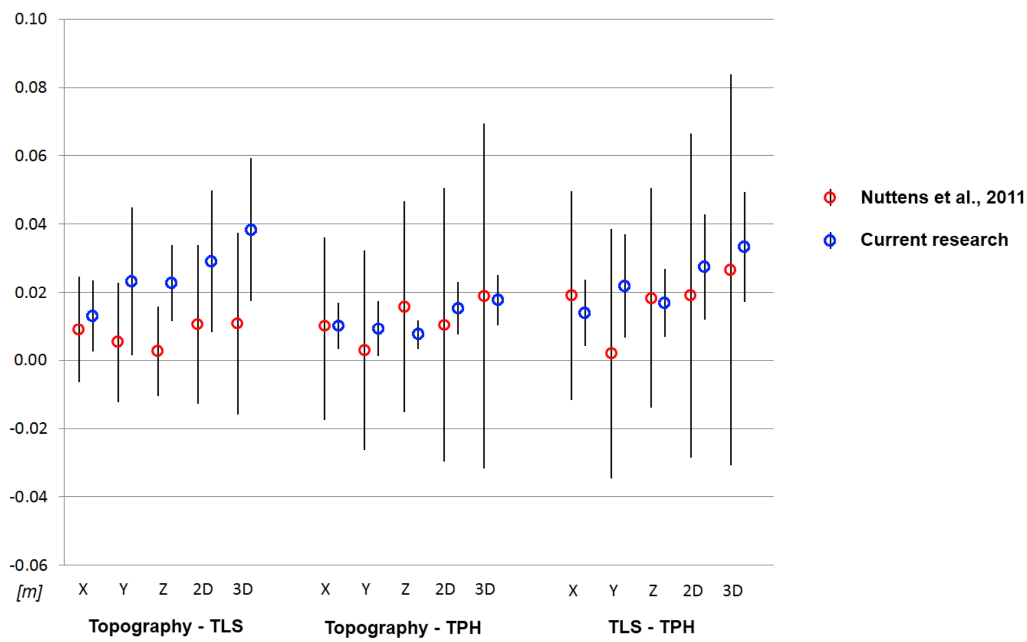


*Figure 5: Pair wise comparison of the current and previous data sets, visualized by the absolute mean and standard deviation*

## CONCLUSIONS

In this research, the performance of terrestrial laser scanning was analysed in comparison with terrestrial photogrammetry, structure from motion and topography. The focus of this research was the geometric accuracy assessment of terrestrial 3D modelling techniques. This accuracy assessment was performed by the construction of a set of check points, measured by a total station. These points were identified in the terrestrial laser scanning-based point set and the terrestrial photogrammetry-based 3D model. The deviation between these coordinates facilitated the comparative analysis. Based on the statistics of these deviations, it became clear that the mean absolute errors between the techniques do not differ significantly, but that the highest correlation occurs with the terrestrial photogrammetry-based comparisons. This indicates that, also with the commercial introduction of structure from motion, terrestrial photogrammetry is still a very useful technique for the documentation of cultural heritage. Since the different data sets were constructed during two separate phases of the project, it was obvious that the heterogeneity of the operators group had an important influence on the quality of the data.

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